Palais du Pharo
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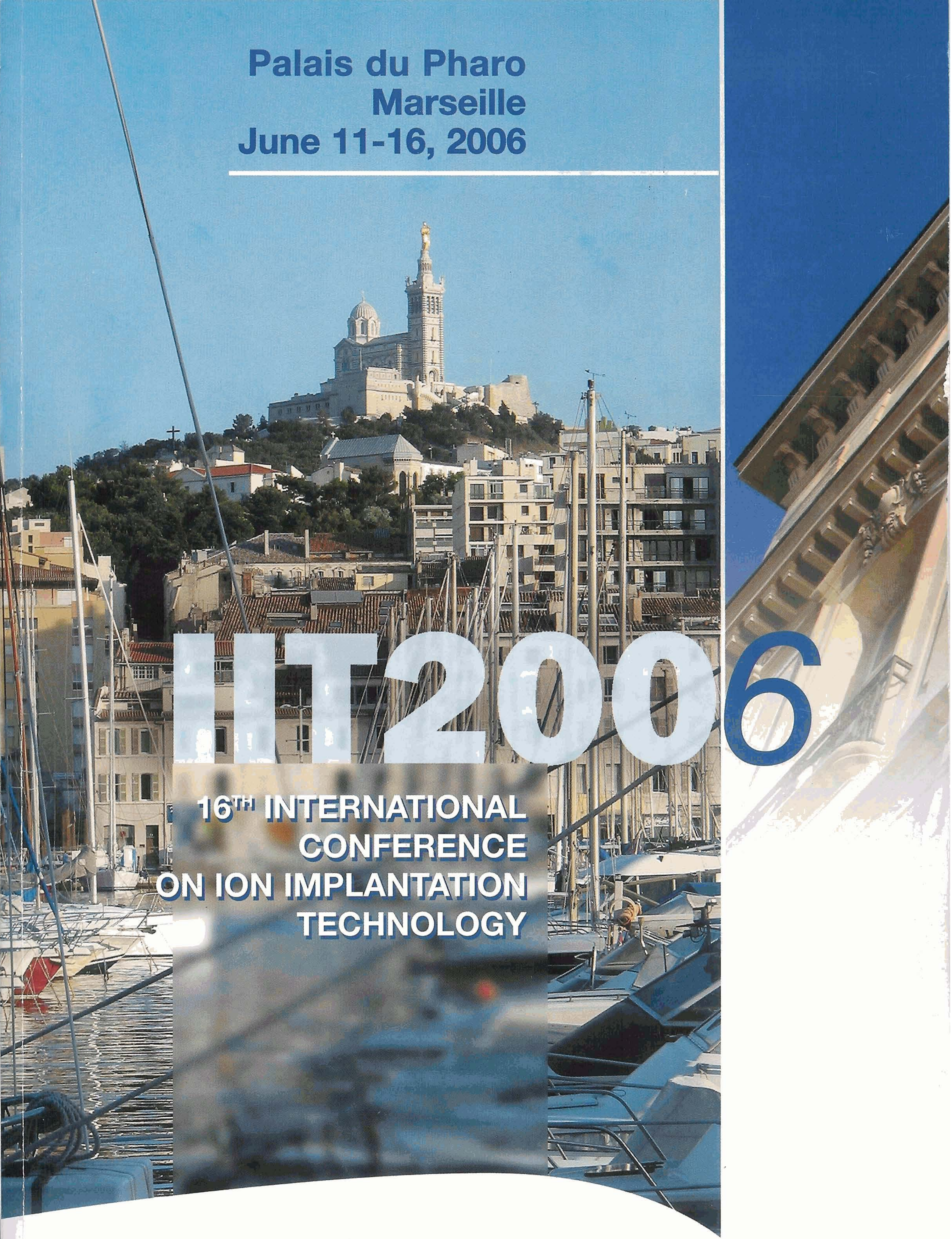
IIT2006

16TH INTERNATIONAL CONFERENCE ON ION IMPLANTATION TECHNOLOGY



Program & Abstracts

Poster Session 2

p207 Numerical Simulation of Plasma Coupling with an External Matching Network by Phasor and Particle Models

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In most of the semiconductor fabrication processes such as plasma doping, plasma-enhanced chemical vapor deposition, and plasma etching, electrical plasma (ions and electrons) are involved. To generate the plasma, it is common to use radio-frequency (RF) coupled inductive or capacitive discharge with an external matching network. Verboncoeur et. al. developed a simultaneous potential and circuit solution for 1D bounded plasma particle simulation. Gauss's law was applied to the plasma system and the second order finite difference equation was derived for the second order Kirchoff's voltage law for a general voltage-driven RLC circuit. However, an external matching network is more complicated than a simple RLC circuit. In plasma processes such as plasma doping, several matching networks with different frequencies may be applied to the electrodes [4]. Solving the second order Kirochoff's voltage equations pertinent to these complicated matching networks is very difficult. An RF signal going through a general matching network can be described by its absolute amplitude and phase. Based on the phasor analysis, any complicated circuits can be described by several linear equations that can be solved directly. In this paper, we describe a model combining the plasma particle model and electrical phasor model, so that the coupling of the plasma with any external matching network can be effectively simulated. The chamber and electrodes, either RF powered or grounded, can be regarded as a good capacitor. In the presence of a semi-ionized plasma, the ions are in room temperature and the electrons are in thermal equilibrium of a few eV in temperature. The accumulated surface charges and consequently the potential are modified by the plasma. Using this model, the amplitude and phase of the voltage/current of the external matching network are numerically estimated, and an auto-matching network is also simulated.

ION IMPLANTATION TECHNOLOGY

16th International Conference on Ion Implantation Technology

IIT 2006

Marseille, France *11 – 16 June 2006*

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L.C. Catalog Card No. 2006935319
ISBN 978-0-7354-0365-9
ISSN 0094-243X

CD-ROM available: ISBN 978-0-7354-0366-6

Printed in the United States of America

Modified Phasor-Particle Model of Treating A Blocking Capacitor As A Phasor Element in Simulation of Plasma Coupling with An External Auto-Matching Network

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Abstract. A phasor-particle model has been developed to numerical simulated the radio-frequency (RF) capacitive coupling between an external matching network and a low pressure electrical plasma [1]. Gauss's law was applied to the blocking capacitor in this model. Non-linearly current was observed flowing into the blocking capacitor [1]. A new method of treating the blocking capacitor as a phasor element is developed such that identical current is flowing through the blocking capacitor. A big impact on the circuit voltages and currents are observed when simulating the asymmetric system by the new method. The proposed method can be applied to quasi-matching condition.

Keywords: Phasor model, Auto-matching, plasma simulation, capacitive coupling.
PACS: 52.65.-y, 52.65.Rr, 52.65.Ww

INTRODUCTION

A phasor-particle model was developed to numerical simulated the radio-frequency (RF) capacitive coupling between an external matching network and a low pressure electrical plasma [1]. In this model, the external matching network or any complicated circuit is modeled by electrical phasor [1]. The chamber and electrodes, either RF powered or grounded, can be regarded as a good capacitor. The accumulated surface charges of the electrode and consequently the potential are modified by the plasma. The plasma is simulated by a one dimension hybrid particle-in-cell (PIC) ions and Boltzmann distribution of electrons [2,3]. The advantage of this model is that any complicated external network can be described by several linear equations that can be solved directly [1]. The amplitude and phase of the voltage/current of the external matching network were numerically estimated, an auto-matching network was simulated, the negative direct current (DC) biased voltage of an asymmetry system associated with a blocking capacitor was generated by this model [1,4].

The schematic of the model simulating an asymmetric system with a blocking capacitor connecting to a matching box was depicted in Fig. 1. An alternate voltage source Vs of absolute value 300 volts, radio frequency of 13.56 MHz with input resistance Ro equal to 50 ohms was connected to an asymmetric chamber represented by a cylindrical capacitor. The outside cylinder of radius r_b equal to 0.2 meter was grounded. The power was transferred to the inner electrode of radius r_a equal to 0.1 meter. The cylinders had a length of 0.2 meter given the chamber capacitance of 16.05 pF.

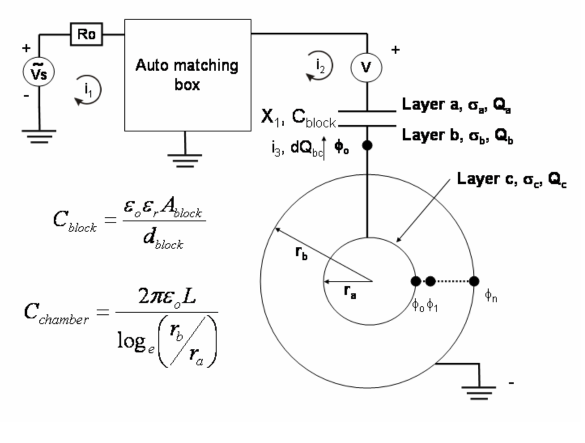

FIGURE 1. The schematic of the asymmetric system with the blocking capacitor is depicted. The chamber is presented by two cylinders of radius r_a and r_b with length L.

A capacitor C_{block} of 200 pF was used to block direct current from flowing into the circuit. An uniform electrical Ar^+ plasma of density equal to 1.0×10^{16} m^{-3} was initially filled up the chamber. The

CP866, *Ion Implantation Technology,*
edited by K. J. Kirkby, R. Gwilliam, A. Smith, and D. Chivers

ions were at room temperature and given a zero initially velocity. The ions were mainly driven by electric field. The electrons were in thermal equilibrium and was described by Boltzmann distribution [1-3]. The distance between the two electrodes was divided into uniform cells of length equal to 1 mm given a total of 100 cells. 1000 PIC particles were uniformly placed in each cell given a total of 100,000 PIC particles. The time step was equal to an RF cycle divided by 200, i.e., $dt=3.68732\times10^{-10}$ seconds. The simulation ended at 20 μsec. The blocking capacitor C_{block} was modeled by applying Guass's Laws to the three layers a, b, and c as depicted in Fig. 1 [1]. The current i_3 between the blocking capacitor and the top electrode was defined as dQ_{bc}/dt as depicted in Fig. 1. At 5 μsec, a negative dc biased voltage of -116 volts was observed at the inner electrode of the system as depicted in Fig.2a. The calculated loading resistance R_L was equal to 162 ohms [1]. However, the current i_2 flowing between the matching box and the blocking capacitor was difference from i_3, the current flowing between the inner electrode and the blocking capacitor as depicted in Fig. 2b. Talking Vs as the reference, it shown that i_1, the current flowing before the matching box, was 7.2° or 0.13 radians behind Vs with amplitude of 3.38 amps, i_2 was 50.4° or 0.88 radians behind with an amplitude of 1.71 amps, and i_3 was 27° or 0.47 radians behind with an amplitude of 1.98 amps. According to the circuit or phasor theories [5,6], it is abnormal to have a difference currents flowing through the blocking capacitor, since it is common treating the blocking capacitor as a circuit element. In circuit model approach [6], a difference current can flow into the ion sheath regions but not for the blocking capacitor. The aim of this work is to investigate the cause of the mismatched between i_2 and i_3 in the previous approach by applying three times Gauss's Law at the three layers. A difference approach of simulating the blocking capacitor will be used. In the new approach, the blocking capacitor is treated as a circuit element and combined into the phasor equations. In other words, we are forcing identical current flowing through the blocking capacitor. The proposed method will be described in the next section. It will be validated by simulating an asymmetric system with an empty chamber. Finally, the simulation results of modeling the asymmetric system coupling with a plasma will be presented and discussed.

SINGLE CURRENT LOOP FOR THE BLOCKING CAPACITOR

In the new approach, the blocking capacitor C_{block} is treated as a phasor element X_1 of value

$$X_1 = \frac{-j}{\omega C_{block}} \tag{1}$$

where $j=\sqrt{-1}$. We can derive a new phasor equation as;

$$V = \varphi_0 + I_2 X_1 \tag{2}$$

Solving with the previous complex number form of the phasor equation [1],

$$V = VsB - I_2 A \tag{3}$$

gives

$$\varphi_0 = VsB - I_2 A' \tag{4}$$

where $A' = A + X_1$. The phasor elements A and B are derived from the matching box [1]. It was shown that under matching condition, the phase of A θ_A is always equal to zero [1]. In real number form, it becomes

$$\begin{aligned}\phi_0 &= |B||V_s|\cos(\omega t + \theta_B) \\ &\quad - |I_2||A'|\cos(\omega t + \theta_2 + \theta_{A'})\end{aligned} \tag{5}$$

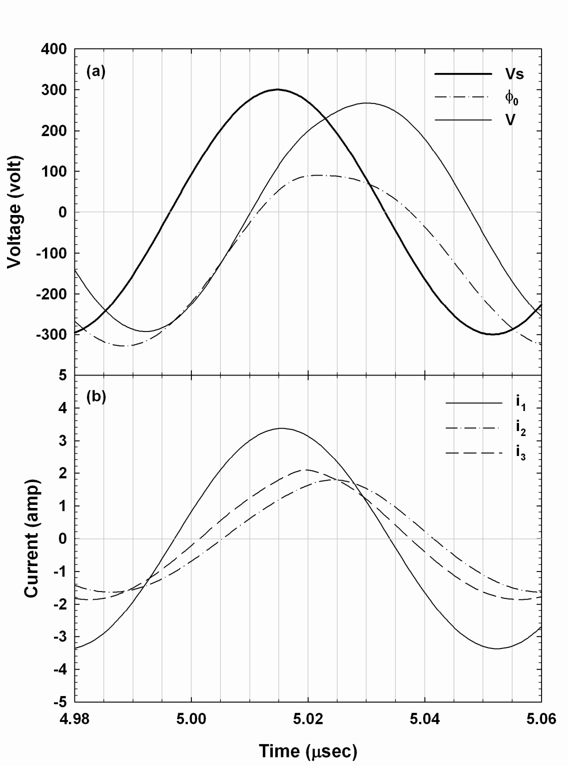

FIGURE 2. The voltages Vs, ϕ_0, and V at 5 μsec are plotted in (a). The currents i_1, i_2, and i_3 at 5 μsec are plotted in (b). The simulation was conducted by applying Gauss's law at the two layers of the blocking capacitor.

The phase of A' $\theta_{A'}$ is not equal to zero even under matching condition. The electrode potential $\phi_0(t)$ can be calculated by another formula [1],

$$\phi_0(t) = \phi_0(t-\Delta t) + \frac{i_2(t)\Delta t}{C_{chamber}} \tag{6}$$

With the presence of a plasma, it is modified as,

$$\phi_0(t)=\phi_0^p+\frac{i_2(t)\Delta t}{C_{chamber}} \qquad (7)$$

where ϕ_0^p is calculated from the Gauss's law [1,7],

$$\phi_0^p=\phi_1+\frac{\Delta r}{\varepsilon_o}\left(\sigma_c+\rho_0\frac{\Delta r}{2}\right) \qquad (8)$$

where ϕ_1 is the potential of the next node, σ_c is the surface charge density (Cm^{-2}), ρ_0 is the charge density of the plasma at the node (Cm^{-3}), Δr is the length of a cell, and ε_o is the dielectric constant. Combining Eqns. (5) and (7) gives,

$$\phi_0^p+\frac{i_2(t)\Delta t}{C_{chamber}}=|B||V_s|\cos(\omega t+\theta_B) \qquad (9)$$
$$-|I_2||A'|\cos(\omega t+\theta_2+\theta_{A'})$$

If $\theta_{A'}$ is equal to zero, the current can be directly solved by,

$$i_2(t)=\frac{|V_s||B|\cos(\omega t+\theta_B)-\phi_0^p}{|A'|+\dfrac{\Delta t}{C_{chamber}}} \qquad (10)$$

For finite $\theta_{A'}$, we rewrite Eqn. (9) as

$$\phi_0^p+\frac{i_2(t)\Delta t}{C_{chamber}}=|B||V_s|\cos(\omega t+\theta_B)-|I_2||A'|(\cos(\omega t+\theta_2)\cos(\theta_{A'})-\sin(\omega t+\theta_2)\sin(\theta_{A'})) \qquad (11a)$$

$$\phi_0^p+\frac{i_2(t)\Delta t}{C_{chamber}}=|B||V_s|\cos(\omega t+\theta_B)-|A'|\cos(\theta_{A'})i_2(t)+|I_2||A'|\sin(\omega t+\theta_2)\sin(\theta_{A'}) \qquad (11b)$$

After rearrangement, it gives

$$i_2(t)=\frac{|V_s||B|\cos(\omega t+\theta_B)-\phi_0^p+|I_2||A'|\sin(\omega t+\theta_2)\sin(\theta_{A'})}{|A'|\cos(\theta_{A'})+\dfrac{\Delta t}{C_{chamber}}} \qquad (11c)$$

At the start of the simulation within 3 cycles, the $|I_2||A'|\sin(\omega t+\theta_2)\sin(\theta_{A'})$ term of Eqn. (11c) is ignored giving

$$i_2(t)=\frac{|V_s||B|\cos(\omega t+\theta_B)-\phi_0^p}{|A'|\cos(\theta_{A'})+\dfrac{\Delta t}{C_{chamber}}} \qquad (12)$$

The amplitude $|I_2|$ and phase θ_2 of the current i_2 are estimated from the previous cycle. After 3 cycles, Eqn. 14c is introduced in the simulation. To make the transformation less chaotic, $|I_2|$ and θ_2 are calculated from an average of two cycles, i.e., the previous cycle and the cycle before the previous cycle. Once i_2 is estimated, V, ϕ_0, and i_1 follow [1].

The method was validated by simulating the asymmetric system as depicted in Fig. 1 with an empty chamber, i.e., no plasma was presented inside the chamber. It was shown that an empty chamber was a good capacitor [1,7] and the asymmetric system with a blocking capacitor was modeled by pure phasor equations [1]. The currents at 5 μsec of a pure phasor model of the asymmetric system with a blocking capacitor of 200 pF were plot in Fig. 3a. The voltage source Vs was also plot as a reference. In the pure phasor model, it was assumed that only one current loop i_2 flowed in loading circuit. The currents at 5 μsec of the proposed method were plot in Fig. 3b. The simulation went into steady state in one μsec that $|I_2|$ and θ_2 did not vary at all. The currents at 5 μsec of the method by applying Gauss's laws to the blocking capacitor were also plot in Fig. 3c. Without the presence of the plasma, the current i_2 overlapped i_3. There was hardly a difference between Fig. 3a, 3b, and 3c. It was also founded that the proposed method had an error of 1% [1]. The error was calculated by dividing the average power deposited to the chamber, 4.70 watt (in principle it should be zero), with the average power input from the source, 649.2 watt. Therefore, the proposed method was validated with a 1% error and will be used to simulate the asymmetric system coupling with a plasma.

SIMULATION RESULTS WITH THE PRESENCE OF A PLASMA AND DISCUSSION

The validated proposed method was used to simulate the asymmetric system with the presence of a plasma. The cylindrical chamber was also filled up with an uniform electrical Ar^+ plasma of density equal 1.0×10^{16} m^{-3}. The temperature was chosen to be 3.0eV. The simulation lasted for 20 μsec. Steady state was acquired after one μsec. The voltages at the electrode ϕ_0, V, the applied potential Vs, the currents i_1, and i_2 at 5 μsec were plotted in Fig. 4. A negative DC bias of -63.3 volt was observed at the electrode potential ϕ_0. A negative DC bias of -113.0 volt was also observed at the potential between the matching box and blocking capacitor V. It was different from the previous founding as depicted in Fig. 2a. A negative DC bias was never observed at the potential V. Moreover, a positive DC current bias of 0.47 amps was observed at the current i_2 as depicted in Fig. 4b. No bias in currents was observed as depicted in Fig. 2b although the currents i_2 and i_3 did not match each other. A big impact on the circuit voltages and currents was observed when a single current loop was assumed flowing through the blocking capacitor. In a non-linearly system, it is no guarantee that an uniform current shall flow into the system. We believe our previous method of applying Gauss's law to the layers of the blocking capacitor is a more appropriate approach. Experiment will be conducted to confirm the findings.

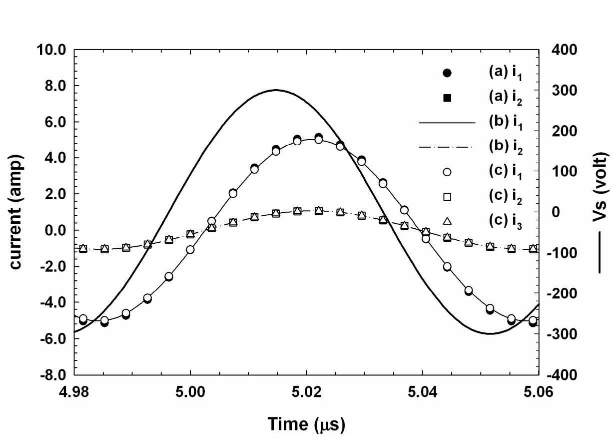

FIGURE 3. The currents i_1, i_2, and i_3 at 5 msec simulated from (a) pure phasor equations, (b) treating the blocking capacitor as a phasor element with an empty chamber, and (c) applying Gauss's law at the blocking capacitor layers, are plotted. The apply voltage Vs are plotted as reference.

CONCLUSION

Numerical simulations of treating the blocking capacitor as a phasor element such that a single current was flow through it in an asymmetric system of plasma coupling with an auto-matching network were carried out. To overcome the problem that the current $i_2(t)$ can not be solved directly with a finite phase $\theta_{A'}$ in Eqn. (9), a modified equation (11) was used. The amplitude $|I_2|$ and phase θ_2 were estimated from the previous cycle. The proposed method was validated by simulating the asymmetric system with an empty chamber. It was founded 1% error was associated with the proposed method. The modified Eqn. (11) can be used to handle quasi-matching condition when the phase θ_A of Eqn. (3) is finite. A negative bias was observed at V, the voltage between the matching box and blocking capacitor, and a positive bias was observed at i_2, the single current loop flowing through the blocking capacitor, by the proposed method. The findings are different from our previous results and experiment has to be conducted to confirm the results.

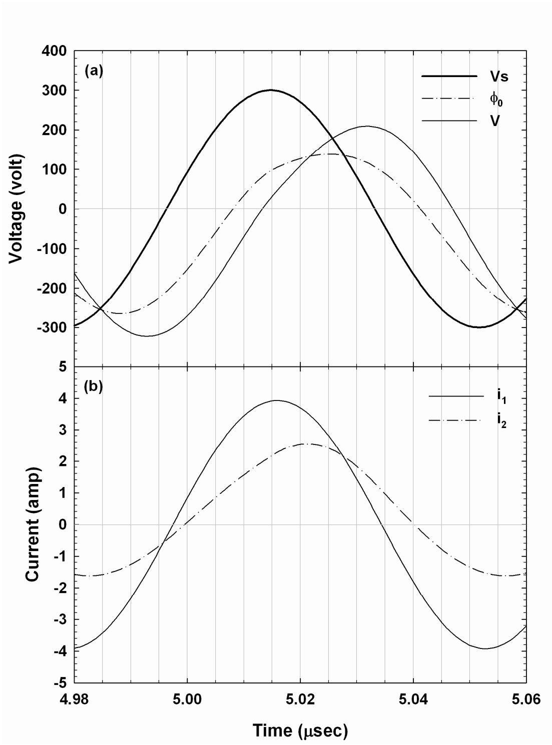

FIGURE 4. The voltages Vs, ϕ_0, and V at 5 μsec are plotted in (a). The currents i_1, and i_2 at 5 μsec are plotted in (b). The simulation was conducted by treating the blocking capacitor as a phasor element assuming identical current flowing through it.

ACKNOWLEDGMENTS

Dixon T. K. Kwok was supported by the Denison Fellowship of the School of Physics, University of Sydney. This work was supported by City University of Hong Kong Strategic Research Grant (SRG) #7001981. The authors appreciated the helpful discussion from Dr. Yongbai Yin.

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